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14. ABSTRACT
The main objective of the research was to provide scientists with a clearer understanding of the relative importance of the physical mechanisms involved in the recovery of the ocean from a cold wake formation, and to provide additional value and insight to the observations already being undertaken by the ITOP program. This was performed by one-dimensional and three-dimensional modeling of the region before, during, and after Typhoon Fanapi.

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Analysis of Mixing and Dynamics Associated with the Dissolution of Hurricane-Induced Cold Wakes

Final Technical Report

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LONG-TERM GOALS

The main objective of the research was to provide scientists with a clearer understanding of the relative importance of the physical mechanisms involved in the recovery of the ocean from a cold wake formation, and to provide additional value and insight to the observations already being undertaken by the ITOP program.

OBJECTIVES

Our approach is to take our version of CUPOM that has been adapted for idealized simulations, use in a realistic setting based on the ITOP field program during and after Typhoon Fanapi and conduct a series of experiments aimed at understanding the relative roles of the surface forcing, wave-induced mixing and other turbulent processes, and horizontal eddy actions at the mesoscale and submesoscale regimes in affecting the recovery of the ocean from the tropical cyclone.

APPROACH

The approach used a high-resolution ocean model (a hybrid version of CUPOM), and idealized and realistic simulations of cold wakes and observations from the ITOP field campaign to investigate the restratification processes affecting cold wakes.

TASKS COMPLETED

The CUPOM model has been run under a variety of simulations, including both realistic forcing and sensitivity analyses. The use of realistic forcing and initial conditions required a number of adjustments. The realistic forcing required a blending of COAMPS winds and OAFlux surface variables (see Figure 1 for resulting hybrid forcing data). Our initial simulations were performed using temperature and salinity profiles from uCTD data obtained during the R/V Revelle cruise. However, these data, even at a fair distance from the eye of the storm, still evidenced the mixed layer temperature and salinity profiles associated with incidents of strong mixing – the mixed layer depths were already at 100 m. Thus, although we had mixing associated with the storms down to 100+m, little cooling occurred since no entrainment was happening. Thus we have had to work with the global HYCOM

model simulations to use for our initial profiles (with ML depths closer to 50 m) rather than the observations. This has resulted in much improved model simulations.

Using this data, we have performed a number of both one-dimensional simulations and three-dimensional ocean model simulations using the realistic forcing and initial stratification. Some key results of the modeling are shown below, in comparison with turbulence measurements. We worked with L. St. Laurent and S. Jayne to add value to the turbulence measurements by focusing on the following key science questions in our models:

(1) What is the relative importance of key mixing mechanisms that are evident in enhanced levels of dissipation near the surface relative to deeper measurements (momentum/wave forcing, inertial oscillations, and heat loss)?
(2) Observations during ITOP clearly demonstrated the importance of multiple features driving restratification of the cold wake, and have investigated the importance of the surface heat flux, submesoscale variability, and mesoscale shear in both idealized cold wake scenarios and those corresponding to the measurements during the ITOP field campaign.

RESULTS

Some sample results from the one-dimensional simulations in comparison with dissipation measurements have been performed and are described here. Figure 2 is one such set of temperature and dissipation variability from a point near the center of the storm and a location that was sampled in situ. Extended mixing to > 100 m is evident, and enhanced dissipation is seen near the surface and at depth for several days following the storm (more on this below).

Sea surface temperatures in this region drop by about 2.5°C, but within 4 days of the passage of the storm the peak daily sea surface temperatures are comparable to prior the storms passage; however, the nocturnal SSTs and the ML temperatures do not recover to their pre-storm values (in part due to seasonally-reduced heat flux) within the next month.

For comparison with the observed dissipations (from L. St. Laurent) we have plotted the integrated dissipation as a function of time (Figure 3). Note that the observations do not have values from the upper 10 m, so here we plot the model simulations both with and without the upper 10 m. The extent to which mixing is occurring below 10 m during and immediately after the storm (September 18 here) is evidenced by the nearly consistent values between 0 – 100 m and 10 – 100 m; after the storm passes dissipation is decreased below 10m relative to the surface. Both profiles evidence a drop-off in dissipation of several orders of magnitude, with the drop-off being greater below the surface. The first observation at roughly 3 days past the storm is comparable in value to the model, with the model decrease larger (background mixing in the one-dimensional model is reduced compared to observations, as no internal waves and similar 3-D structures are evident). As with the observations, the model demonstrates an enhanced level of dissipation that is commensurate with the winds picking up again on September 24. The model presents a clear picture of a decrease in dissipation in the upper 100 m of over 4 orders of magnitude from the peak of the storm through the next 5 days, until winds pick up somewhat again, confirming the speculation that much of the dissipation that had occurred with the storm had been lost within the next two days (by again roughly 4 orders of magnitude).

We have begun experimenting with evaluating the role of heat fluxes vs. momentum fluxes in driving the dissipation results. For one set of simulations the heat flux during the three weeks just prior to, during, and after the typhoon was reduced by varying amounts; the results with a 50% reduction in heat flux loss (but solar radiation unchanged) is shown in Figure 4. The SST drop was roughly equivalent during the storm, but SSTs recovered to pre-storm values within 4 – 5 days. The integrated dissipation remained roughly equivalent. That the main contributor to the change in temperature of the upper ocean was the entrainment generated by momentum fluxes rather than convection is evident by contrasting the results when heat fluxes remain as observed but momentum fluxes are reduced by 50% (Figure 5). The SST drop is less than 2°C, the mixed layer depth increase is substantially reduced, and the entire upper 50 m remains much warmer.

Our initial results thus highlighted the role of momentum and entrainment towards enhancing mixing and sea surface temperature variability in a one-dimensional series of simulations. It should be noted that including Langmuir circulation and an idealized wave field made little difference to the overall results outside of the very uppermost meters. At least in the one-dimensional model simulations, the cold wake recovery itself depends mainly on the heat/momentum flux environment after the storm itself.

We then performed a series of three-dimensional model simulations in order to investigate the above observations within a fully realistic model. The CUPOM model was run using the Kantha-Clayson mixing scheme including Langmuir circulations. The horizontal resolution was roughly 10 km and the vertical had 38 layers. For reasons discussed above, we used a spatially uniform set of temperature and salinity profiles, where the values above 200 m were a composite of the pre-typhoon CTD casts from ITOP, and below 200 m WOA climatology was used. The surface forcing consisted of the COAMPS winds, FLASHFlux (satellite) radiation (with a horizontal resolution of 1°), air temperature and humidity from OAFlux (horizontal resolution of 1°), SST from the REMSS satellite product (horizontal resolution < 0.1°), and air pressure from the NCEP2 product (horizontal resolution 2.5°). From these we computed interactive turbulent fluxes, in order to couple the ocean cooling in the model with the appropriate fluxes.

Using the realistic forcing conditions, the timing and intensity of the cooling in the model (2.5°) are reasonably well matched to observations (Figure 6). As observed, there is a significant increase in the mixing and cooling on the rightward side of the storm. The model simulations also demonstrate that the decay of exceptional mixing occurs very rapidly (Figure 7). The 0 – 100m integrated dissipation scales very tightly to the approach and decay of the storm (Figure 8), and a dropoff begins immediately after the storm, which approaches a decay of four orders of magnitude. The three-dimensional simulations show that the dissipation on the north (or right side of the storm) is roughly twice that of the south (or left side) of the storm, partly due to the greater depth of mixing on that side (Figure 9). Note that for comparison we have plotted both the 0 – 100 m integrated dissipation and the 10 – 100 m integrated dissipation. The turbulence measurements of L. St. Laurent and others during the storm (shown again in Figure 8) do not include data closer to the surface than roughly 10 m. The model 10 – 100m integrated dissipation results for the time periods and depths of the observations correspond quite closely. However, some additional features are evident in the model simulations. The first is that since we capture the increase of mixing over the life cycle of the storm, which allows us to observe the increase in mixing by four orders of magnitude tied directly to the timing of the storm, and the immediate decay thereafter. The observations of dissipation nearly three days past the passage of the storm, while allowing for some observations of the decay of dissipation, are too late to catch all but one order of magnitude of decay, and also miss the rapid decline from the moment of the storm

passage. In addition, the model simulations also reveal that the largest percentage of the turbulence induced by the storm occurs within the upper 10 m, as 0 – 100m integrated dissipation is an order of magnitude higher than the 10 – 100m integrated dissipation. Furthermore, all of these observations are similar between the north and south of the storm (although the dissipation is roughly twice the total on the north (right) side of the storm, rates of change are similar between the two sides).

A number of sensitivity studies were run with varying surface forcing. Two of the simulations are shown here, encapsulating the results. The first simulation shown was determined by reducing the total heat flux lost by the ocean during the passage of the storm by 50%. As can be seen in Figure 10, reducing the total heat flux has negligible effect on the drop in SST, and almost no change in the recovery. However, a 50% drop in momentum flux has a much stronger effect on the simulations. The SST decrease is smaller (due to the decreased deepening of the mixed layer), and the entire upper 50 m remains much warmer than in the control simulation. However, the rate of recovery is consistent between all three of the simulations, consistent with the recovery being an internally-generated ocean relaxation. As with the temperatures and mixed layer depths, changes in heat flux made little to no difference in the mixing (Figure 11), while the decrease in momentum flux accounted for an overall decrease in dissipation. The rate of change of mixing and the timing of the increase/decrease in mixing is consistent, indicating that while the magnitude of the increase and decrease will depend to some degree on the magnitude of the surface forcing (particularly the momentum flux), there are also a number of similarities and generalizations that can be drawn. It should be noted that the overall results were also not extremely dependent on the inclusion of Langmuir circulation and wave-induced turbulence, and our initial 1 km simulations demonstrated changes in the long-term recovery of the cold wake, but did not affect the magnitude or time-scale of the orders of magnitude dissipation variability in the days before, during, and immediately after the passage of the storm.

Similarities and differences between the three-dimensional and one-dimensional model simulations should be mentioned. Both sets of simulations demonstrated that entrainment was the major contributor towards change in the upper ocean temperature. However, differences were apparent in the mixing rates and character. It should be noted that the mixing model is the same between the one-dimensional and the three-dimensional model, as is the initialization and forcing. Thus, any differences in the model simulations has to do with the inclusion of the fully three-dimensional circulations that occur. In the one-dimensional model, the mixing rates between either the 0 – 100 m integrated values or the 10 – 100 m integrated values were essentially the same, while in the three-dimensional model there was an order of magnitude difference. Also, in the one-dimensional model simulation, the drop in dissipation is too great (compared with the observations), particularly at depth. The three-dimensional model simulations are more consistent with the observations.

IMPACT FOR SCIENCE

(1) Variability seen in turbulence observations of the upper ocean during a typhoon can be realistically reproduced within the current generation of high-resolution ocean mixed layer models, particularly in models with the full complement of three-dimensional processes.

(2) The rate of decrease in mixing remains consistent under a number of scenarios, and may indicate that even with incomplete or inferior-quality surface forcing parameters, estimates of the change in dissipation may still be roughly accurate. A more definitive statement would require more sample sets, but the initial results are encouraging for those estimating dissipation and variability due to typhoon cold wakes.

(3) Dissipation rates above 10 m are dependent on three-dimensional ocean processes, in addition to local instantaneous mixing, and are at least an order of magnitude greater than in those depths more commonly measured. However, at least from our simulations, the ratio of the upper dissipation to the lower dissipation remains constant throughout the time period before, during, and after the typhoon, and even under varying strengths of the typhoon. Thus, it may be possible to estimate with some accuracy the surface dissipation even if only observations below 10 m are available.

RELATIONSHIPS TO OTHER PROGRAMS

The observations of other ITOP researchers, in particular the dissipation measurements of L. St. Laurent, were vital towards determining the validity of the model mixing simulations. At the same time, the model simulations were able to provide additional value to the observations by providing more context for the possible universality of the data, as well as elucidating the mixing in the upper surface layer.

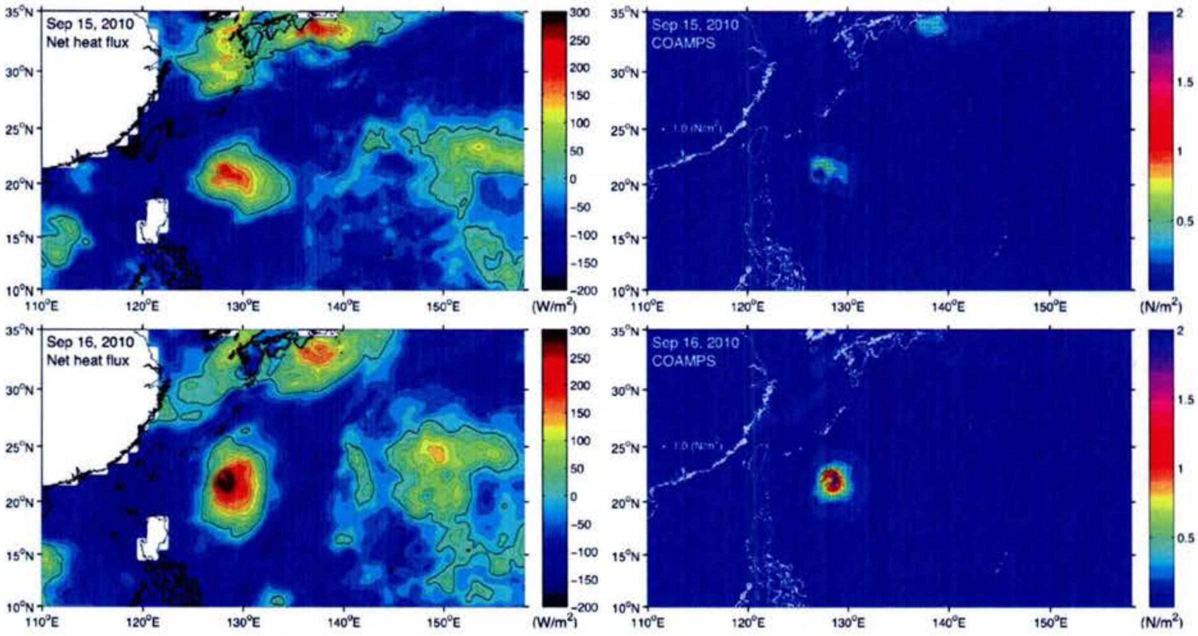

Figure 1. Representative forcing of net het flux and wind stress, hybrid values using COAMPS output and OAFlux (satellite and reanalysis) data.

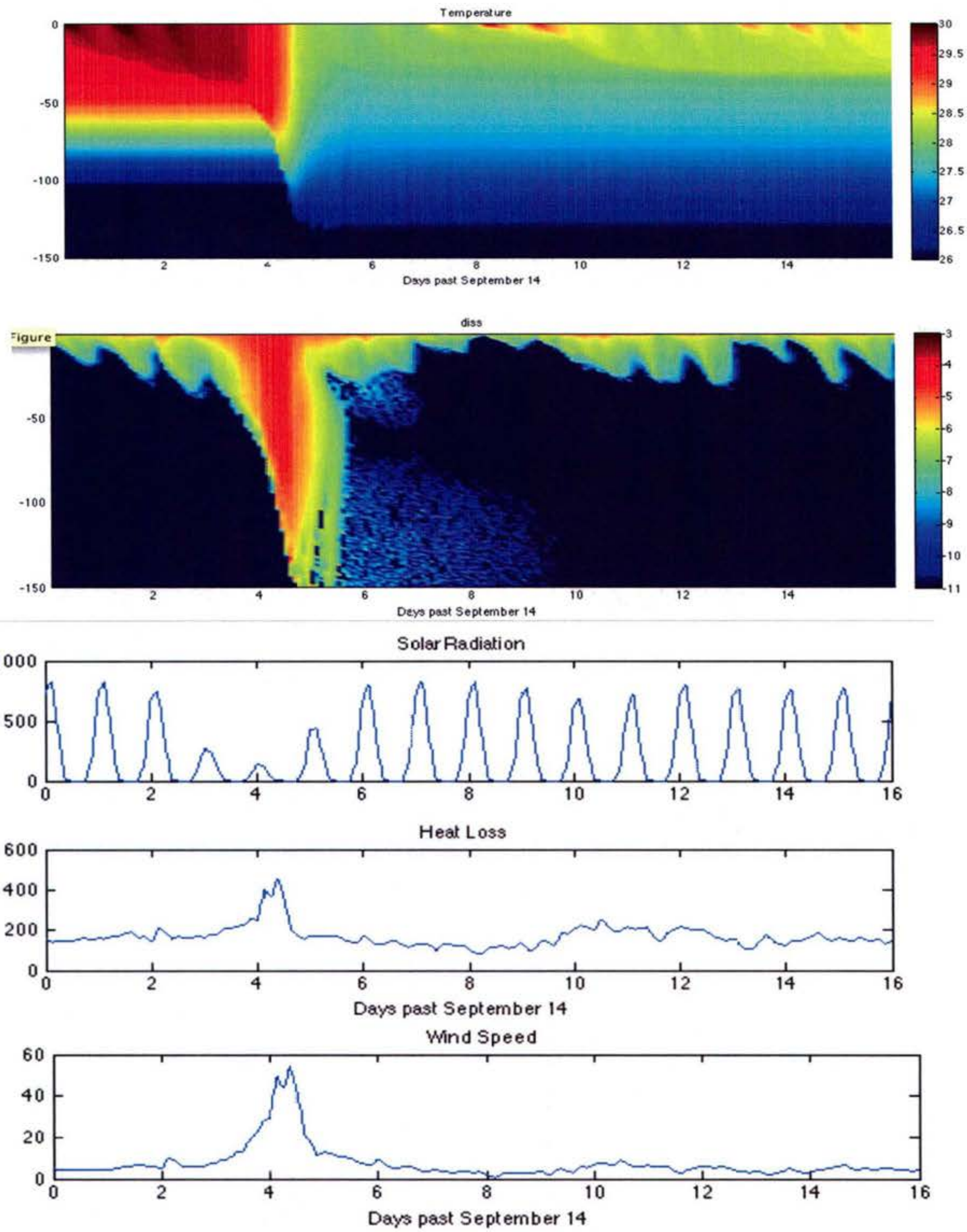

Figure 2. One-dimensional model simulations of the temperature (top) and dissipation (bottom). Days noted are number of days after September 14. Also shown for comparison are the heat fluxes and winds during this time period.

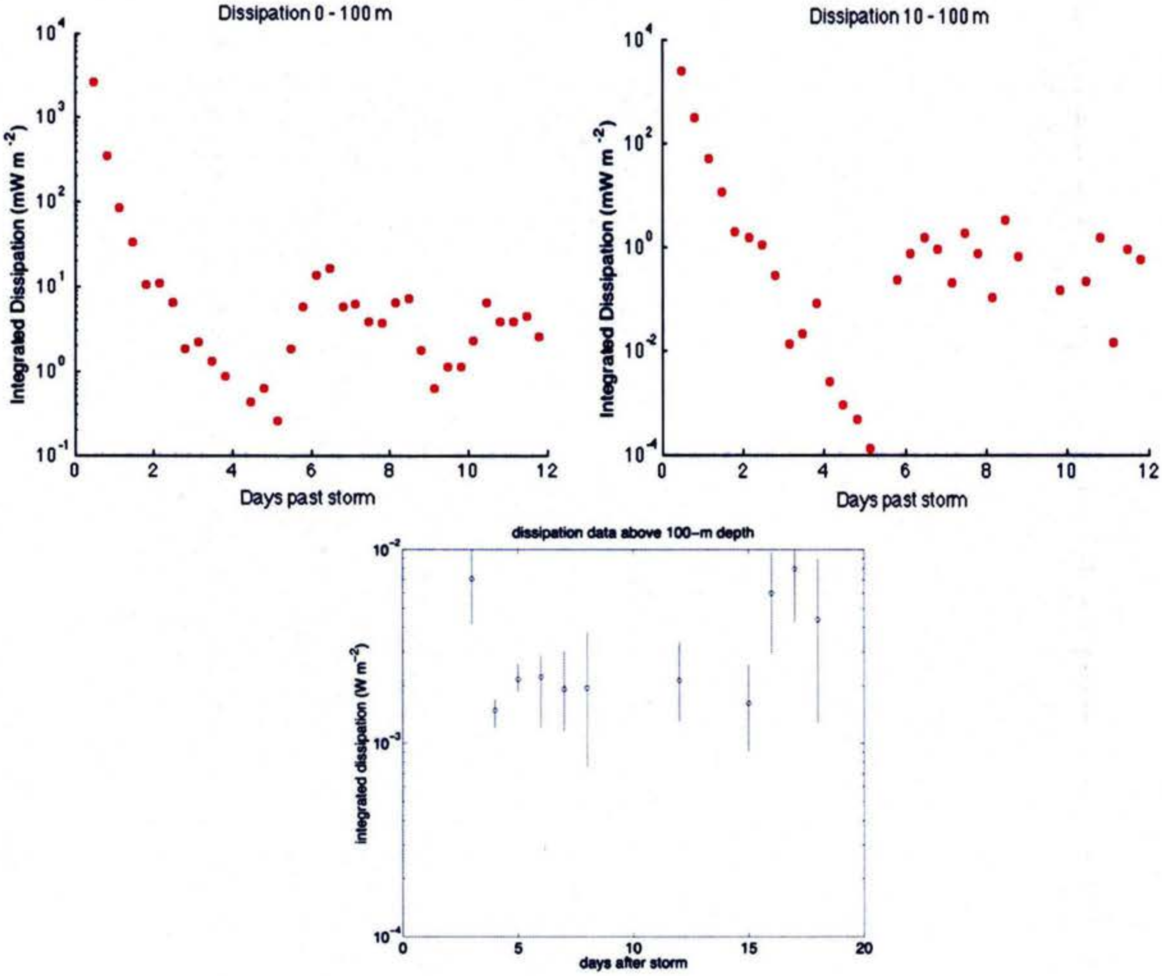

Figure 3. Model simulations of the integrated dissipation (top) and observed integrated dissipation from L. St. Laurent (bottom). Days noted are number of days after September 14.

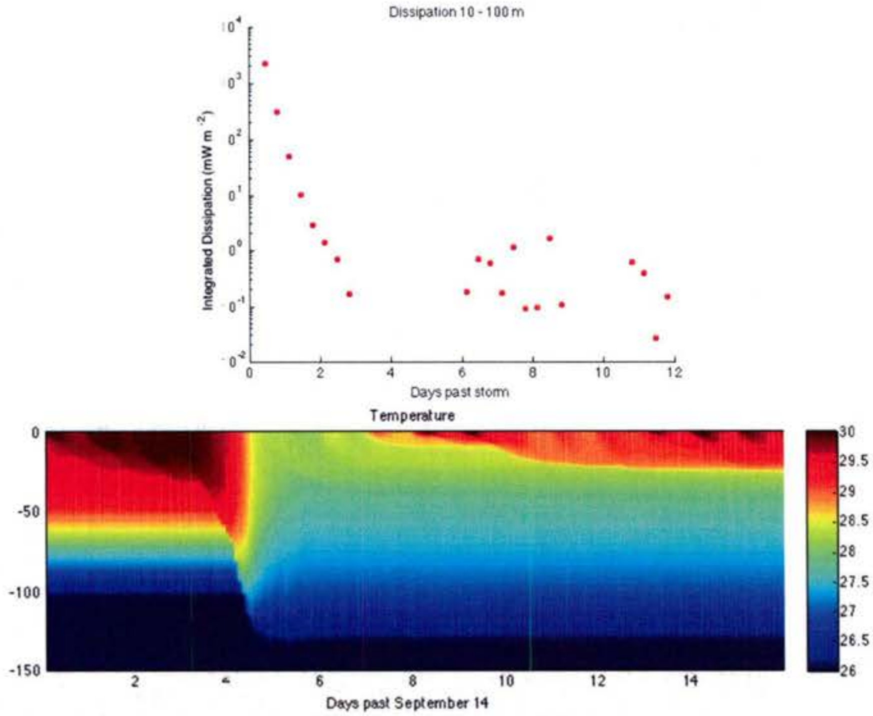

Figure 4. One-dimensional model simulations of the integrated dissipation (top) and temperature (bottom) for a 50% reduction in heat flux are shown. Days noted are number of days after September 14.

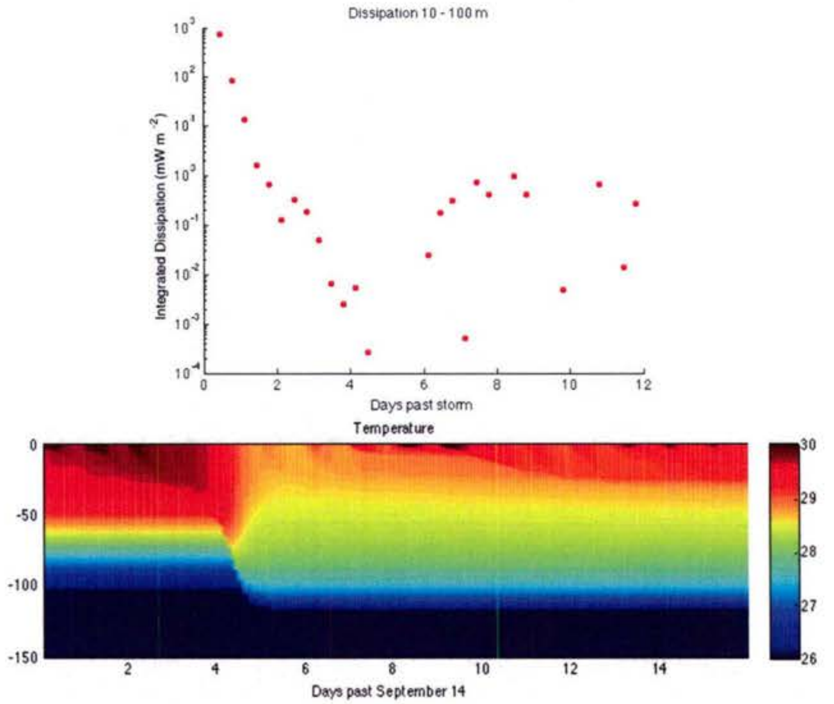

Figure 5. One-dimensional simulations of the integrated dissipation (top) and temperature (bottom) for a 50% reduction in momentum f.ux are shown. Days noted are number of days after September 14.

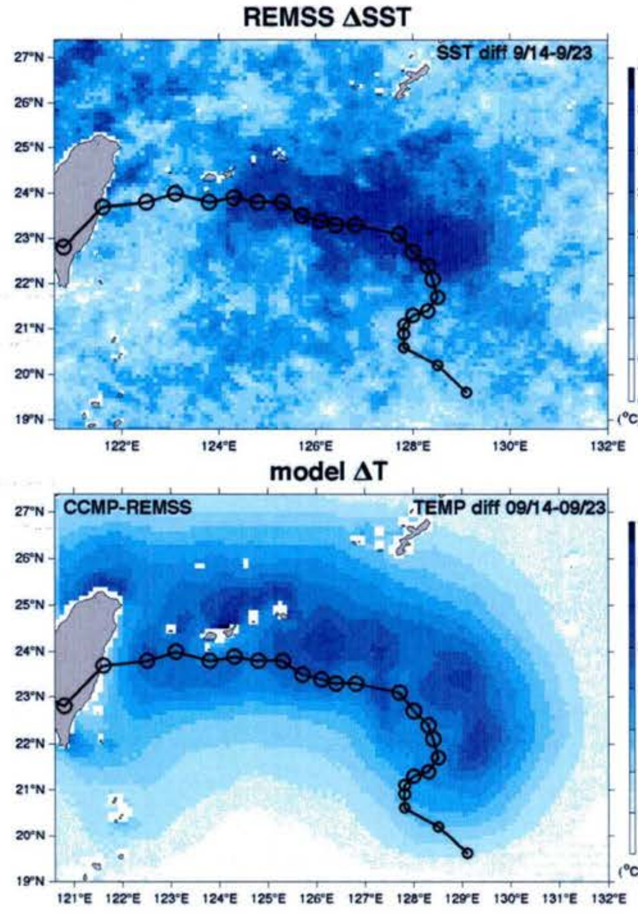

Figure 6. Satellite SSTs (upper panel) and model simulation SSTs (bottom) changes in temeprature over the time period of Fanapi passage. Differences between the two are in part due to the relatively coarse flux forcing (1 degree resolution). Model resolution in these figures is 10 km.

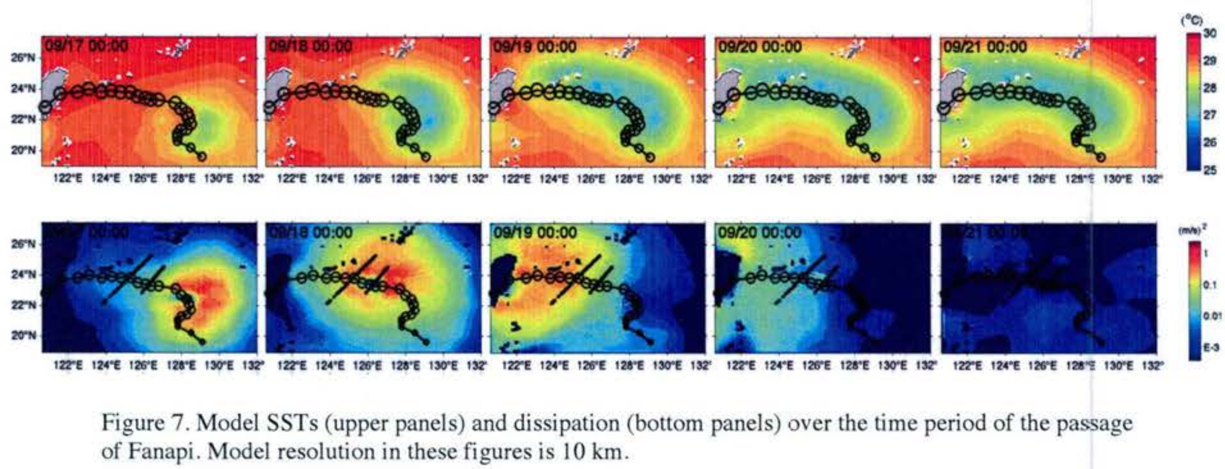

Figure 7. Model SSTs (upper panels) and dissipation (bottom panels) over the time period of the passage of Fanapi. Model resolution in these figures is 10 km.

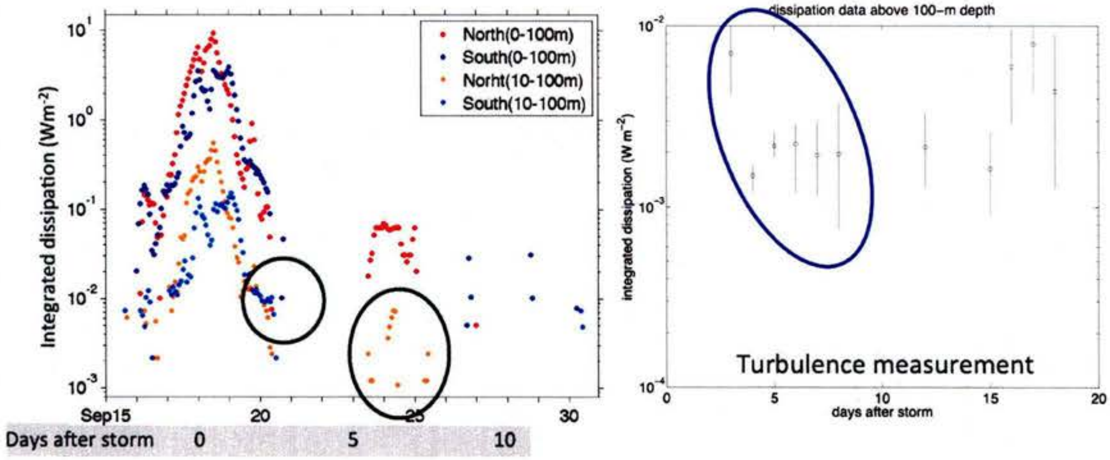

Figure 8. Modeled integrated dissipation (left panel) and observed integrated dissipation (right panel). Note the rapid onset and then decay of enhanced TKE over the upper nearly 100 m, consistent with observations when observations are available.

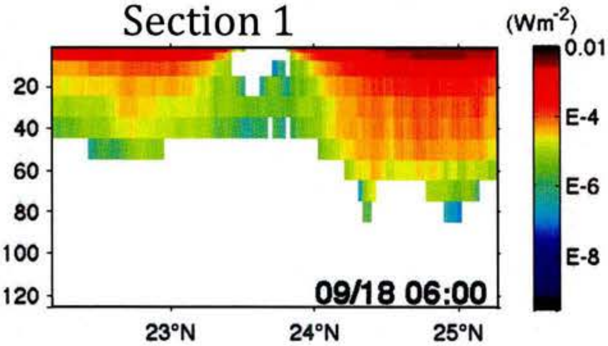

Figure 9. Modeled enhanced TKE at the time of typhoon passage, with stronger and deeper mixing occuring to the right of the storm.

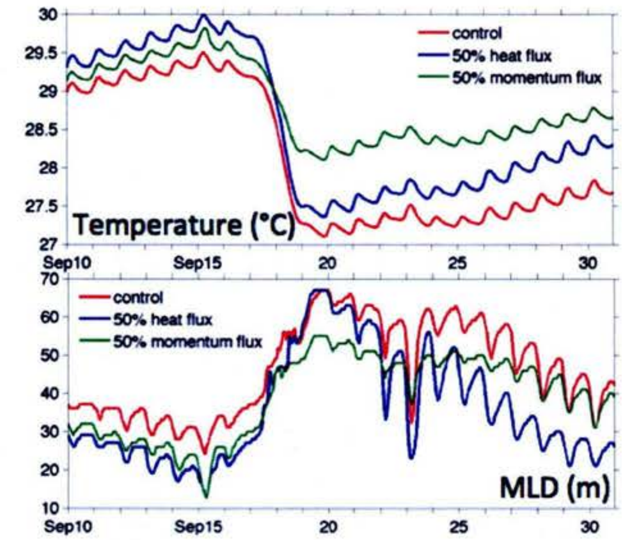

Figure 10. Sea surface temperature (top panel) and mixed layer depth (bottom panel) variability evolution between the realistic forcing (control) and changes to the heat and momentum fluxes.

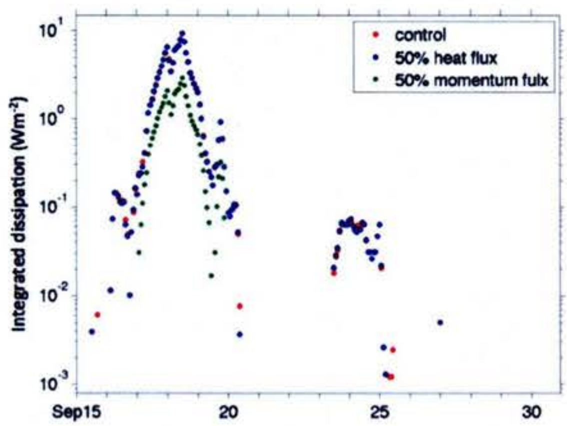

Figure 11. Total integrated dissipation from 0 – 100 m evolution between the realistic forcing (control) and simulations with changes to the heat and momentum fluxes.